

Determining gravitational lensing effects on supernovae observations

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In this paper we use a generalized version of a method originally proposed by Holz and Wald [1] to investigate the effects from gravitational lensing on Type Ia supernovae measurements. We find that results for different mass distributions in smooth dark matter halos are very similar, making lensing effects predictable for a broad range of density profiles. Also, a sample of 100 supernovae at $z \sim 1$, should be sufficient to discriminate between the case of all dark matter in smooth halos and the extreme case of all dark matter in point-like objects.

1. Introduction

Gravitational lensing has become an increasingly important tool in astrophysics and cosmology. In particular, the effects of lensing has to be taken into account when studying sources at high redshifts. In an inhomogeneous universe, sources may be magnified or demagnified with respect to the case of a homogeneous universe with the same average energy density.

Holz and Wald (HW; [1]) have presented a method for determining gravitational lensing effects in inhomogeneous universes. Their use of realistic galaxy models has been limited to the singular, truncated isothermal sphere (SIS) with a fixed mass. We have generalized their method to allow for matter distributions more accurately describing the actual properties of galaxies. The list of matter distributions have been extended to include the density profile proposed by Navarro, Frenk and White (NFW; [2]) and we use a distribution of galaxy masses. Also, other matter distribution parameters such as the scale radius of the NFW halo and the cut-off radius of the SIS halo are determined from distributions reflecting real galaxy properties. For further details we refer to Bergström *et al.* [3] where also the method of HW has been generalized to allow for general perfect fluids with non-vanishing pressure.

As an application of the method, we investigate gravitational lensing effects on observations of distant supernovae. Specifically, we consider

the effects on supernova luminosity distributions.

2. Method

The method of HW can be summarized as follows: First, a Friedmann-Lemaître (FL) background geometry is selected. Inhomogeneities are accounted for by specifying matter distributions in cells with energy density equal to that of the underlying FL model. A light ray is traced backwards to the desired redshift by being sent through a series of cells, each time with a randomly selected impact parameter. After each cell, the FL background is used to update the scale factor and expansion (see Fig 1). By using Monte Carlo techniques to trace a large number of light rays, and by appropriate weighting [1,3], statistics for the apparent luminosity of the source is obtained.

3. Gravitational lensing of supernovae

One of the major goals of cosmology is to determine the cosmological parameters of our Universe. It has been realised that observations of supernovae at high redshift can be used for this purpose, in particular for determining the value of the cosmological constant. In fact, several collaborations with this in mind are in progress, and the first sets of data show an intriguing hint of a non-vanishing cosmological constant [4,5].

Although the two groups which have published results mutually agree on the best-fit parameters, it is important to note that the effects of geome-

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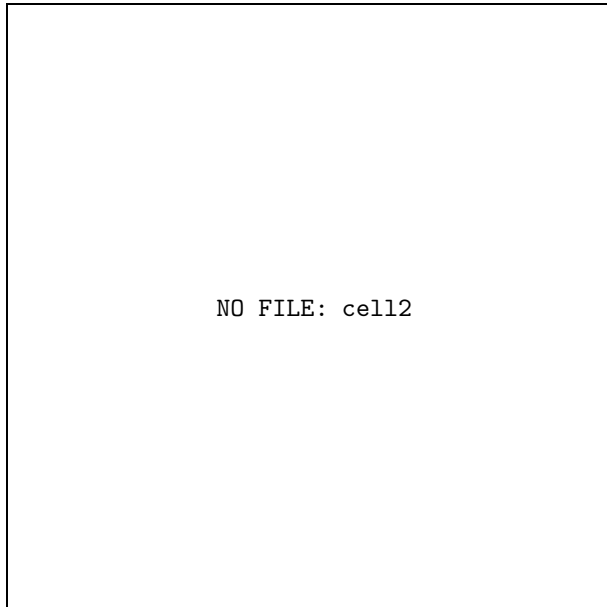


Figure 1. In the method of HW, light rays are traced backwards to the desired redshift by being sent through a series of cells, each time with a randomly selected impact parameter.

try are small (on the order of half a magnitude), and the need to go to even higher redshift to get larger effects is obvious. When observing such distant sources, at redshift greater than unity, it is necessary to estimate the effects of lensing due to inhomogeneities in the matter distribution. In Fig. 2, we compare the effects from gravitational lensing with the intrinsic dispersion of Type Ia supernovae. It is evident that gravitational effects become comparable to the intrinsic dispersion at redshifts larger than one.

Of course, the additional dispersion caused by gravitational lensing will be a source of systematic error in the cosmological parameter determination with Type Ia supernovae. However, a possible virtue of lensing is that the distribution of luminosities might be used to obtain some information on the matter distribution in the Universe, see Goliath and Mörtzell [6].

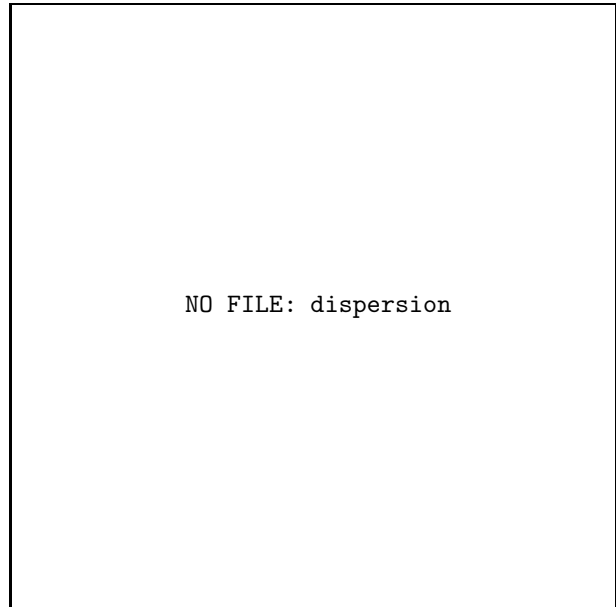


Figure 2. Luminosity distribution for 10 000 sources in an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ universe with 80 % isothermal spheres and 20 % compact objects. Note that lensing effects become comparable to the intrinsic dispersion of Type Ia supernovae at redshifts larger than one.

4. Results

In Fig. 3, we compare the luminosity distributions obtained with point masses, SIS lenses and NFW matter distributions in an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ universe, currently favoured by Type Ia supernova measurements [4,5] and anisotropy measurements of the cosmological background radiation [7,8]. Sources are assumed to be perfect standard candles. The magnification, given in magnitudes, has its zero point at the filled beam value, i.e., the value one would get in a homogeneous universe. Note that negative values corresponds to demagnifications and positive values to magnifications. Results for SIS halos and NFW halos are very similar, even when we have no intrinsic luminosity dispersion of the sources.

In Fig. 4 we have added an intrinsic luminosity

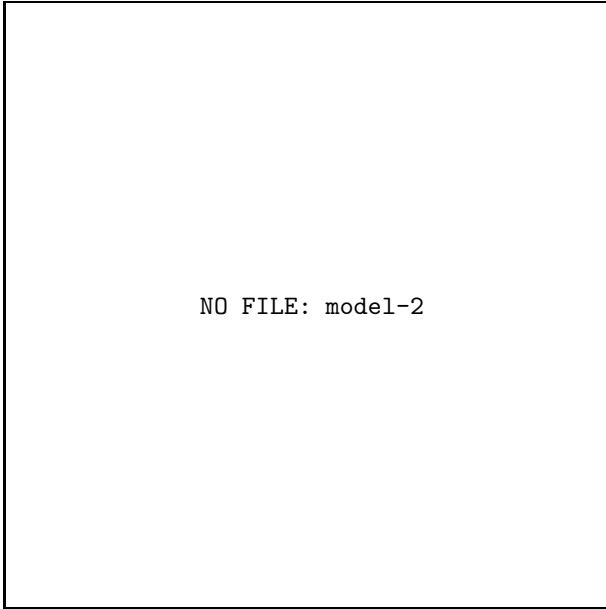


Figure 3. Luminosity distributions for 10 000 perfect standard candles at redshift $z = 1$ in an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ universe. The magnification zero point is the luminosity in the corresponding homogeneous (“filled-beam”) model. The full line corresponds to the point-mass case; the dashed line is the distribution for SIS halos, and the dotted line is the NFW case.

dispersion represented by a Gaussian distribution with $\sigma_m = 0.16$ mag., due to the fact that Type Ia supernovae are not perfect standard candles. The effect is to make the characteristics of the luminosity distributions even less pronounced, since the form of the resulting luminosity distributions predominantly is determined by the form of the intrinsic luminosity distribution. It is still possible to observationally distinguish whether lenses consist of compact objects or smooth galaxy halos (see also [9,10]). Generating several samples containing 100 supernova events at $z = 1$ in an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology filled with smooth galaxy halos, we find that for 98 % of the samples one can rule out a point-mass distribution

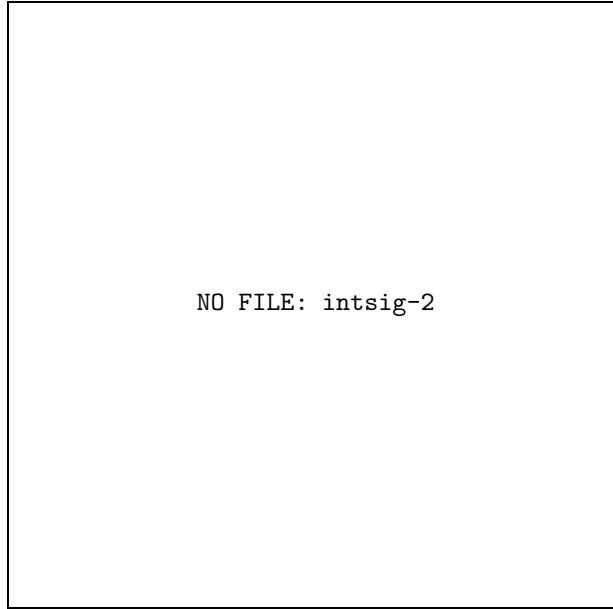


Figure 4. Luminosity distributions for 10 000 sources at redshift $z = 1$ in an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ universe. This is the same situation as depicted in Fig. 3, only that we have added an intrinsic luminosity dispersion of the sources with $\sigma_m = 0.16$ mag. (corresponding to the case of Type Ia supernovae).

with 99 % confidence level². Furthermore, for a similar sample containing 200 supernovae, the confidence level is increased to 99.99 %.

A more extensive discussion of the luminosity distributions of perfect standard candles obtained with the different halo models at different source redshifts can be found in [3], where also some analytical fitting formulas for the probability distributions are given.

5. Summary

We have generalized the method of Holz and Wald [1] to allow for matter distributions reflecting the actual properties of galaxies. One of the

²However, in 1 % of the samples, we will erroneously rule out the halo distribution with the same confidence level.

virtues of this method is that it can be continuously refined as one gains more information about the matter distribution in the universe from observations. The motivation for these generalizations is to use this method as part of a model for simulation of high-redshift supernova observations, *the SuperNova Observation Calculator (SNOC)*.

In this paper, we have considered lensing effects on supernova luminosity distributions. Results for different mass distributions in smooth dark matter halos were found to be very similar, making lensing effects predictable for a broad range of density profiles. Furthermore, given a sample of 100 supernovae at $z \sim 1$, one should be able to discriminate between the case with smooth dark matter halos and the (unlikely) case of having a dominant component of dark matter in point-like objects.

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